Management of Heterogeneous UAVs Through a Capability Framework of UAV's Functional Autonomy

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Abstract

An increased interest in utilising groups of Unmanned Aerial Vehicles (UAVs) with heterogeneous capabilities and autonomy is presenting the challenge to effectively manage such during missions and operations. This has been the focus of research in recent years, moving from a traditional UAV management paradigm of *n-to-1* (n operators for one UAV, with *n* being at least two operators) toward *1-to-n* (one operator, multiple UAVs). This paper has expanded on the authors' previous work on UAV functional capability framework, by incorporating the concept of Functional Level of Autonomy (F-LOA) with two configurations: The lower F-LOA configuration contains sufficient information for the operator to generate solutions and make decisions to address perturbation events. Alternatively, the higher F-LOA configuration presents information reflecting on the F-LOA of the UAV, allowing the operator to interpret solutions and decisions generated autonomously, and decide whether to veto from this decision.

Keywords: Heterogeneous UAVs, Functional Capability Framework, Autonomy Framework, Functional LOA, Level of Detail (LOD), Information Abstraction (IA).

Introduction

New ways to operate Unmanned Aerial Vehicles (UAVs) have been a challenging focus of research in recent years, as a traditional paradigm of *n-to-1* (n operators for one UAV, with *n* being at least two operators) is driven toward *1-to-n* (one operator, multiple UAVs). As needs are identified that require multiple UAVs, so is there a need to manage UAVs with different capabilities – multiple heterogeneous UAVs. Unmanned Aircraft Systems (UASs) could become groups of simple but complementary UAVs, whose behaviours and capabilities could differ profoundly even when being parts of the same "team", especially in the civilian domain. This means that the operators will have to face new challenges in managing a heterogeneous team of UAVs instead of a one unique and well-defined entity.

UAV heterogeneity can be viewed in three respects; capability heterogeneity – UAVs with a mix of different payload onboard, which forms the different capabilities;

platform heterogeneity – different types of UAVs, possibly with different performances or even vehicle types; and autonomy heterogeneity – UAVs operating at a mixed Level of Autonomy (LOA) [1]. In this paper, the UAV heterogeneity is referring to heterogeneity in LOA.

Background

Past research has looked at many aspects to manage multiple heterogeneous and homogeneous UAVs. These include assessing the mental capacity of an operator to simultaneously control multiple UAVs; utilising system automation to assist with command and control [2]; task scheduling for managing current and future mission schedules [3]; and categorising the UAV's functional capability and selectively displaying these capabilities' to the operator [4].

Cummings and Guerlain [5], and Cummings and Mitchell [6] studied operator mental capacity and demonstrated that an operator has the mental capacity to supervise up to eight homogeneous UAVs under specific mission constraints (e.g. A UAV cannot visit targets which it cannot meet the times on target, and each UAV must visit at least one target etc.). In their research, it was also demonstrated that operator workload can be reduced [5] with assistance from automation.

Other researchers have also investigated supervisory control of multiple UAVs through scheduling of tasks [7]. Task scheduling involves managing the time and information, taking into account the different reaction and wait times of the human mental performance [6], and automatically generates schedules for the machines to perform tasks, thus reducing the operators' workload during a mission [7].

The authors of this paper are investigating the management of multiple UAVs with heterogeneous capability and autonomy through a visualisation method [4]. A framework of the UAV's functional capabilities has been conceived. From this framework, certain elements are selected to be displayed to encourage better mixed-initiative cooperation between human and machine, thus reducing the operators' mental workload in cognising information, while improving their Situational Awareness (SA) of the environment and their assets.

From this, it is visible that one of the fundamental challenges lies in managing multiple heterogeneous UAVs with a mix of LOAs, and it is this challenge that creates the niche. Therefore, this paper presents an extension to the authors' previous work of UAV capability visualisation, by proposing the functional autonomy framework, with the UAVs' autonomy heterogeneity as the focus of the research.

Functional and Capability Framework

The authors of this paper have initially proposed the UAV's functional and capability framework as an index to adaptive information display [4]. Given specific environmental conditions and situations, given to the UAV platforms and capabilities; only the relevant information is selected for display.

The method used to construct the functional and capability framework is based on Information Abstraction (IA) [4].

Information Abstraction

The IA process is similar to Abstraction Hierarchy (AH) [8] used in Work Domain Analysis (WDA) [8], where a hierarchy is formed based on abstracting system functions. In IA, the framework is formed by abstracting UAV systems and subsystems from a very generic and operational perspective.

From this, the capabilities are then indicated by functionality, and as the hierarchy extends further below, each subsystem's functional attributes are displayed. Once the framework is formed using this technique, a method of indexing the level of richness (or simplicity) of information display is required.

Level of Detail

The method used to index the amount of UAVs' functional information display is Level of Detail (LOD). This method was initially proposed by Chen et al. [4]. As the amount of information increases, the LOD index decreases; that is to say, at a less abstract level of information display, the lower the numeric value of the LOD (ie. LOD-1).

As Fig. 1 below illustrates a generic search UAV's functional capability, the different coloured bands indicate the four LODs; green indicates LOD-4, the highest LOD with the most abstracted functional information; lime indicates LOD-3, reasonably abstracted information with some more details; orange indicates LOD-2, again with greater information, less abstracted from the levels above; and finally, red indicates LOD-1, with the most complete and least abstracted UAV functional information.

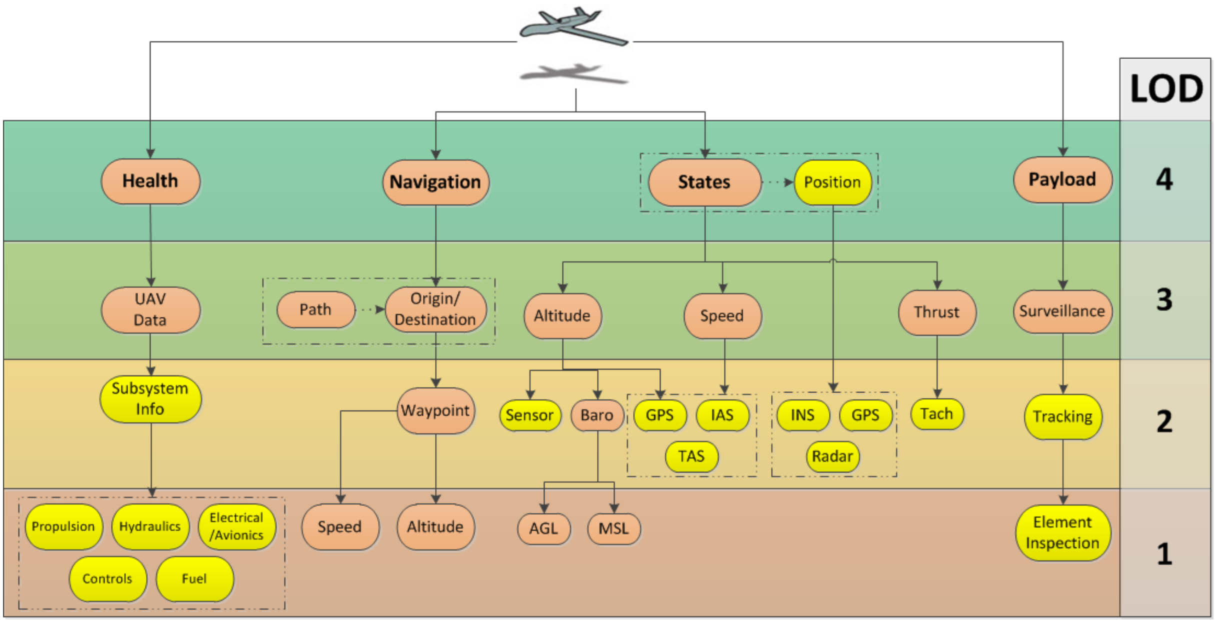

Fig. 1: Functional and capability framework graphical illustration

At different stages of the mission, different LODs will be required depending on the autonomy of the UAVs.

Framework Structure

The framework has four main branches, as shown in
Fig. 1 above. Each of these branches denotes one main system of the UAV. The four main systems of the UAV for this paper are *health, navigation, states,* and *payload*.

Health denotes the health of the UAV subsystems and other forms of onboard system data. This then expands into UAV data, subsystem information, and subsequently, the lower levels of the various subsystem information of the UAV.

Navigation denotes the autonomous navigation ability of the UAV. As this framework will be represented visually on the experimental platform, the navigation structure is broken down into what and how much information will be necessary. As shown, in the lower levels of this branch, detailed textual information will be available for the waypoint, in the form of speed and altitude requirements.

States denotes the position and configuration of the UAV in the air (as a direct meaning of states in aeronautics). The UAV's position information is always available; therefore it is included in the highest LOD. At one lower level, the three states of a UAV are displayed. Continuing one level lower, the different types of each of the three states are also visible. However, there will be no need to continue down to the last LOD, as all critical and detailed information is illustrated at LOD-2.

Payload denotes the operational and functionality of the UAV's payload. Since the UAVs used in this study are homogeneous in type (i.e. they are all rotary winged, surveillance UAVs), there is only one stream of information expanding from the *payload* subsystem main branches and details

This framework can be expanded and reconfigured depending on the requirement of the assets and the mission scenarios, but for the purpose of this study and experiments, the framework is illustrated as above.

Autonomy Visualisation Framework

An extension of the functional and capability framework is the representation of the UAVs' "meta-knowledge" framework, or also known as the autonomy visualisation framework. Through this framework, the operator will receive different levels of visual representation, as represented through the LODs, of the system capabilities reflecting on the UAV's LOAs.

For example, if the state branch (Fig. 2) of the UAV has a lower LOA while other subsystems are functioning with higher LOAs, greater visibility of the UAV state (lower LOD-1 and 2) is presented. This relationship between the UAV's LOA and the LOD, and the way they are communicated back to the operator forms the mixed initiative dialogue.

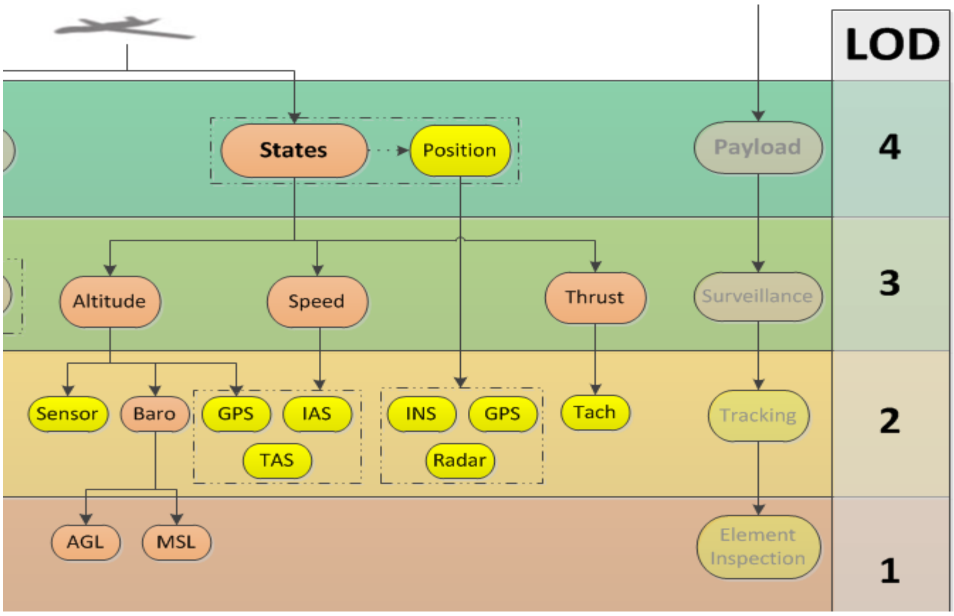

Fig. 2. State Branch of a UAS (an extract of Fig. 1)

"The Meta-Knowledge" on UAVs

The "meta-knowledge" in this study is referring to the collection of the UAV's LOAs. It is to be displayed to the operator in a form of meta-information, that is, non-direct information being displayed through other means. This knowledge can be gathered indirectly by the visualisation of the UAV's functionality.

The extension to the authors' previous work is the method used to communicate this "meta-knowledge" to the operator. The LOA for each function of the UAV can be communicated to the operator through system information visualisation of its functional subsystems. This creates an interface environment where the operator will be able to gather knowledge about the UAVs' autonomy, without directly needing to acquire the specific LOA information.

Functional Level of Autonomy (F-LOA)

In the past, LOA has been used as a scale to describe UAV autonomy [9]. However, through recent studies, it has been established that autonomy should not only be viewed as one feature of a UAV [1], as each UAV has many subsystems and functionalities [4]. Therefore, the concept of Functional LOA (F-LOA) is introduced [4].

F-LOA is used to describe how autonomous a specific functional subsystem of a UAV is, rather than the entire UAV entity described by LOA. In this study, the F-LOA of a UAV can be characterised into four levels; Low Autonomy (LA) – where operator action is the main source of input, Moderately Low autonomy (ML) – this involves some level of machine input, Moderately High autonomy (MH) – a large amount of machine solution generation, with the operator making final decision, and High

Autonomy (HA) – complete machine input. This LOA structure is similar to that of the Human Automation Collaboration Taxonomy (HACT) [10].

Framework/Model Description

In autonomy display, there are two forms of framework; the initial display framework for lower autonomy (e.g. LA, ML) situations (V), and the display for higher autonomy (e.g. MH, HA) situations (V').

With the lower autonomy situations, the operator will be able to acquire situation knowledge based on perturbation events*, (such as an interruption of the original flight path due to severe turbulence enroute, or a possible collision with high elevation terrains in the flight path) and the* F-LOA *of the UAV, as shown in*
Fig. 3. With a combination of these two attributes (events and F-LOAs), the functional capabilities of the UAV will be visually represented to the operator through the *Capability Framework*.

The visualisation of the lower level F-LOA will present the UAV's functional capabilities at a selected LOD of the UAV (through *Capability Framework*), and the perturbation event (the course) of the environment (through *Event notification*). This will be sufficient to allow the operator to make decisions based on his/her interpretation of the perturbation event.

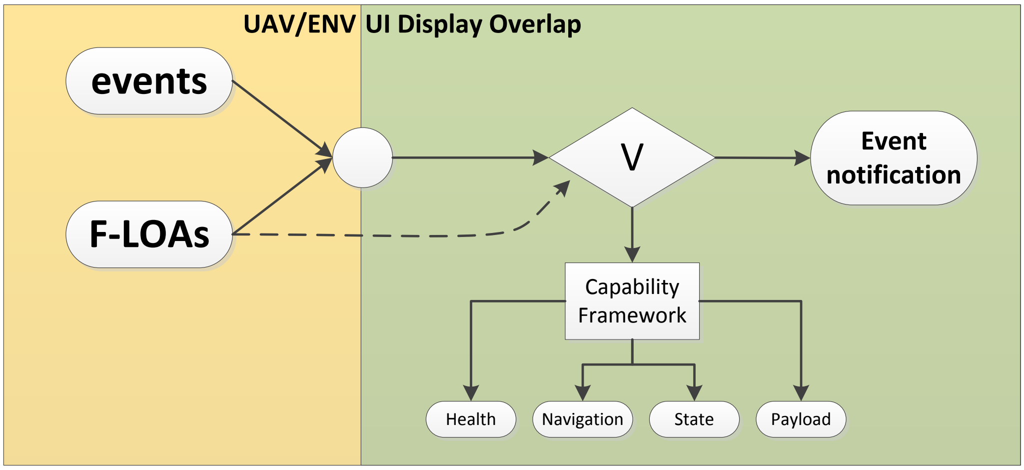

Fig. 3. Display Model of Lower Autonomy Visualisation Configuration

Similarly, for the higher autonomy configuration, this information will also be presented. However, the difference is that this information is now adaptively presented, which means it will be selectively displayed. Due to its higher autonomy, the machine is now capable to generate possible solutions and make decisions based on the environmental and UAV subsystem information. This decision will then be expressed to the operator in a form of *Objective* illustrated in Fig. 4 (such as new flight paths on the map to indicate avoidance of danger). With this information, the operator can make decisions to veto (or not) the machine generated and selected decisions.

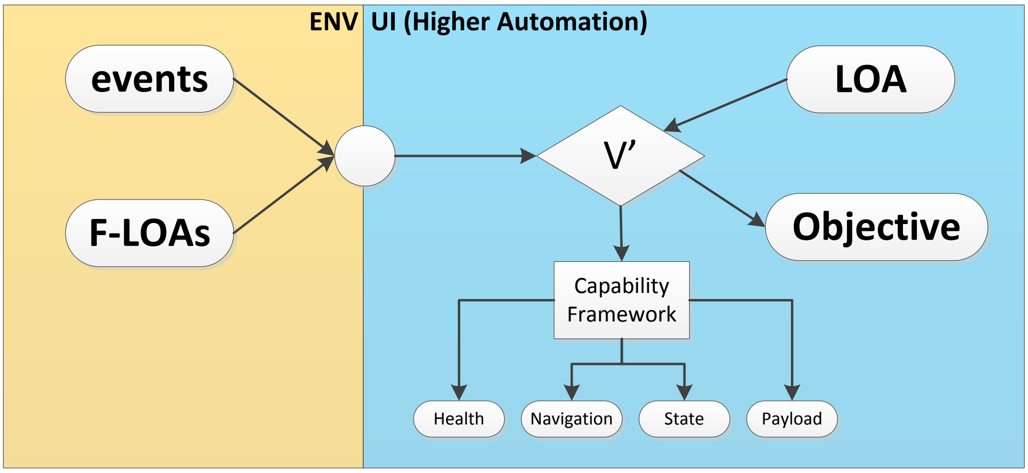

Fig. 4. Display Model of Higher Autonomy Visualisation Configuration

The difference in the visual representation of these modes can be illustrated in Fig. 5. The left illustrates a visual representation of the lower autonomy mode, while the right illustrates the higher autonomy mode.

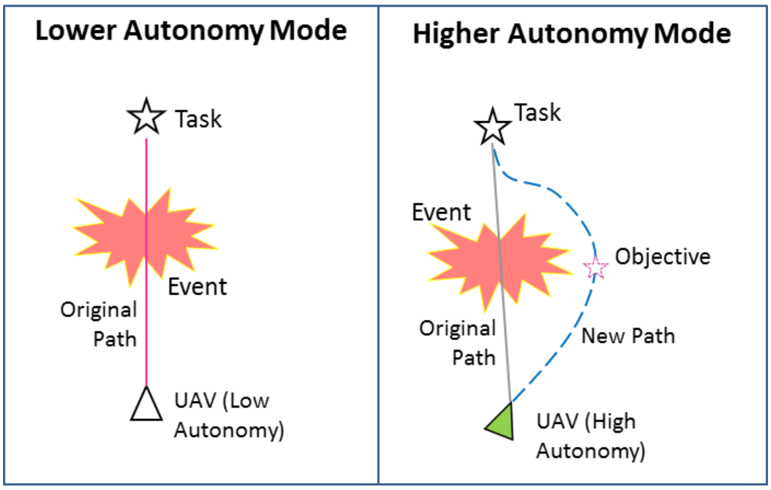

Fig. 5. Comparing Autonomy Mode Configurations: Left – Lower Autonomy Mode Configuration; Right – Higher Autonomy Mode Configuration

As illustrated, the lower autonomy mode displays only the *Event* but no new plans will be autonomously proposed or activated. This provides sufficient information for the operator to take corrective course of action. In the higher autonomy mode (indicated by the green coloured UAV icon), the operator will have the information of the autonomy-proposed and activated course of action to the perturbation events through an objective waypoint. The operator now has the knowledge, and can choose to veto such decision or not.

These modes will then be tested through an experiment conducted on a touchtable. This is to investigate the effect of abstracting the functional information from the UAS to produce the functional capability framework, as well as adaptively displaying the UAV's functionality based on its F-LOA.

Implementation Demonstration

The meta-knowledge framework and LODs described previously have been implemented in a demonstration search and rescue application. This application was developed for the DiamondTouch DT107, multi-user, multi-touch interactive tabletop (Fig. 6 right) [11]. It runs a custom software program in a simulated command and control mission style scenario. Operators perform a search mission for lost people in a designated arena with a number of heterogeneous UAVs with a range of F-LOAs.

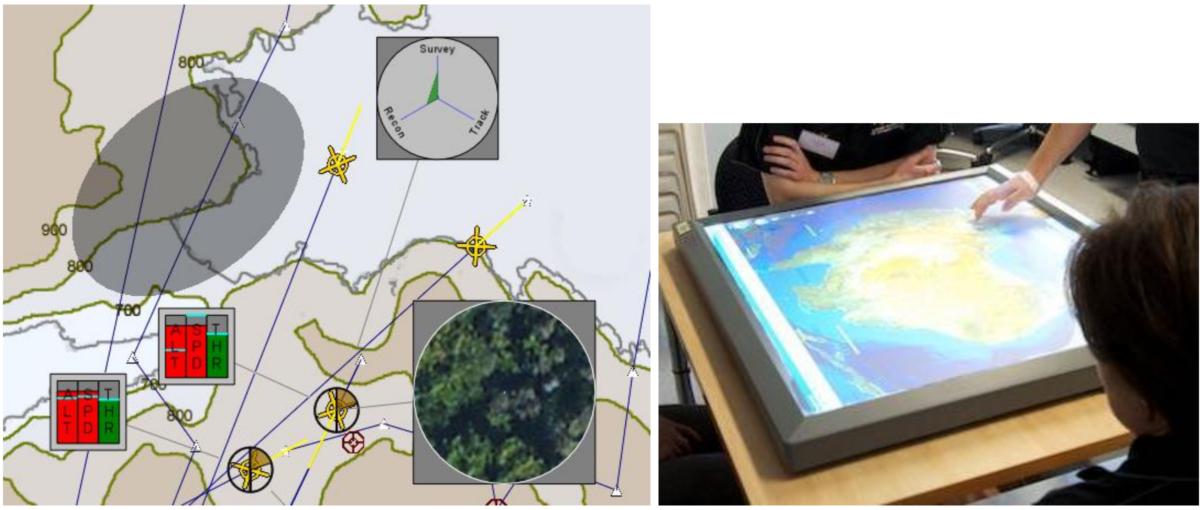

Fig. 6. Left – Experiment Demonstrator Screenshot; Right – DiamondTouch DT107 Multiuser Interactive Tabletop

This scenario is set in a location in the French Alps, involving some mountain ranges and lakes (as shown by the topographical terrain in Fig. 6 left). A number of search zones will involve hypothetical lost personnel which need to be located by the search mission operator (the participant in subsequent experiments).

The demonstrator comprises three segments. The three segments have different modes of interaction with a mix of F-LOA of the UAVs throughout. The example in Fig. 6 left shows two representations of health, one representation of autonomy, and one of payload imagery.

Conclusion

An increased interest in utilising groups of UAVs with heterogeneous capabilities and autonomy is presenting the need to effectively manage such during missions and operations. This paper has expanded on the authors' previous work on UAV functional capability framework, by incorporating the concept of F-LOA. This extension proposes two configurations in the mixed-initiative dialogue: The lower F-LOA configuration contains sufficient information for the operator to generate solutions and make decisions to perturbation events. Alternatively, the higher F-LOA configuration presents information about the functional autonomy of the UAV, allowing the operator to understand solutions and decisions generated autonomously.

This concept has been developed in the described demonstrator in order to improve the operator's SA and reduce their cognitive workload, by presenting only the necessary UAV subsystem information. Future work will consist of conducting an experiment on the demonstrator to confirm this hypothesis.

Acknowledgement

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